6—*Late Quaternary Changes of Sea-Level at Rottnest Island, Western Australia*

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Abstract

Rottnest Island, situated eleven miles off the coast of Western Australia near Fremantle, consists predominantly of dune rock of presumably late Pleistocene age. Some marine limestones, including a fossil coral reef, are probably of slightly greater age. Part of the island is occupied by a series of salt lakes which in early Recent time formed an embayment of the sea. Erosional features such as benches and undercut cliffs as well as the existence of shell deposits at various heights above sea-level suggest lowering of sea-level in the post-Pleistocene of 10-11 feet by two steps interrupted by stillstand periods at about 5 feet and 2 feet above present sea-level.

Introduction

Although Rottnest Island is one of the most popular holiday resorts in Western Australia and within easy reach of Perth and the metropolitan area, no more than passing references to its geology may be found in existing literature. The following notes are the result of two visits to the island in 1938 and 1945, together of about three weeks' duration. Geological observations on the island are facilitated by good maps. A map on the scale 16 chains = 1 inch is available from the Lands Department of Western Australia and during the war the Department of the Army issued a contour map on the scale of 4 inches = 1 mile. A very useful little map, about ½ mile = 1 inch, is on distribution at the Government Tourist Office of Western Australia. Finally, Admiralty Chart 240, "Approaches to Fremantle," was found very helpful; it gives Rottnest Island and surrounding reefs and waters on the scale 2,500 feet = 1 inch.

My thanks are due to Mr. William Brown, now of the Australasian Petroleum Company, Melbourne, who assisted me in various ways on a number of excursions to different parts of the island in December, 1945, and to Mr. Gordon Smith, of the University of Western Australia, who helped to take a line of soundings across Government House Lake. Professor E. de C. Clarke and Dr. R. W. Fairbridge, of the University of Western Australia, had the kindness to read through the manuscript and made a number of valuable suggestions for which I am much indebted to them.

General Description

Rottnest Island lies in the Indian Ocean, eleven miles off the coast of Western Australia, slightly north of the latitude of Fremantle. Its greatest length is in an east-west direction from Philip Point to Cape Vlaming (over 6½ miles), its greatest width in a north-south direction between Parker Point and Point Clune, slightly less than 3 miles. It covers an area of approximately 7 1/3 square miles.

The island rises from the continental shelf inside the 10-fathom line which in this vicinity bulges oceanward to a distance of almost 20 miles from the mainland (fig. 1). The coasts are partly sandy,

but partly formed by cliffs, and the surface of the island is irregularly hilly. The highest elevation is 154 feet, situated almost in the centre of the island and bearing the principal lighthouse, and hills higher than 100 feet are found in many parts of the island.

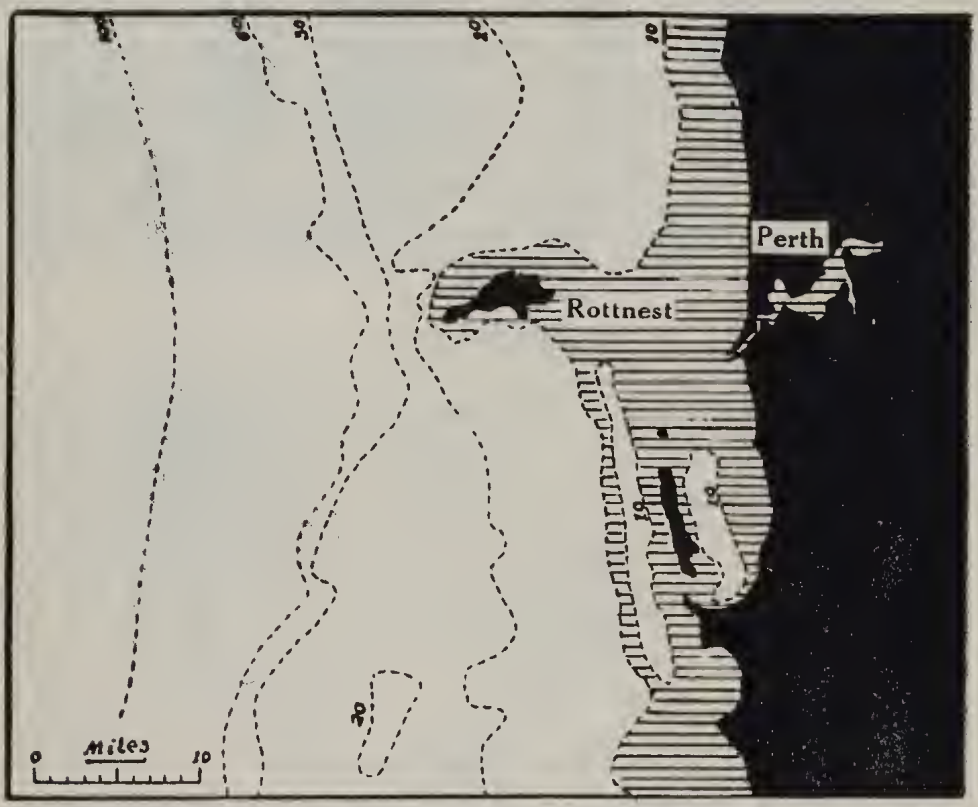

Fig. 1.—Part of the coast of Western Australia, showing mainland coast, shelf, and Rottnest Island. (Depths in fathoms.)

Much of its surface is covered by blown sand, although solid rocks crop out in many places and are exposed intermittently all along the coasts. These rocks are limestones and calcareous sandstones of what in Western Australia is generally known as the "Coastal Limestone Series" and will be described in more detail below.

One of the most attractive features and one to which the island owes much of its popularity as a holiday resort, is a series of salt lakes in the eastern half. There are four principal lakes—Government House Lake, Serpentine Lake, Lake Herschell, and Lake Bagdad—in addition to a few smaller ones. Together the lakes cover an area of about 0.8 square miles, or about one-ninth of the surface of Rottnest Island. A line of soundings taken across Government House Lake indicated the existence of a fairly flat bottom at depths of from 23 to 28 feet.

The water of all the lakes is highly saline. In summer time the lake levels fall, owing to excessive evaporation and the salinity probably increases correspondingly. During the rainy season in winter time the lakes rise and the salinity must be presumed to be lower.

The following analysis of a sample of water taken from Government House Lake on 23rd January, 1940, has been made available by the Rottnest Board of Control:

	‰
Calcium carbonate ($CaCO_3$)	0.37
Calcium sulphate ($CaSO_4$)	4.60
Magnesium sulphate ($MgSO_4$)	11.04
Sodium nitrate ($NaNO_3$)	Nil
Magnesium chloride ($MgCl_2$)	17.19
Potassium chloride (KCl)	3.40
Sodium chloride (NaCl)	108.67
Iron and aluminium oxides (Fe_2O_3 and Al_2O_3)	0.50
Silica (SiO_2)	Traces
Total	145.8 ‰
Total hardness	31.0
Total magnesium	6.6

pH = 8.4.

Encircling the lakes is an almost continuous platform of varying width which is submerged during the wet season, but dry in summer. It is carved out of the dune limestone and its position seems to be at present mean sea-level or very slightly higher. It is covered with fossil shells, mostly gastropods and pelecypods, and shell deposits are also found in the vicinity of the lakes up to a height of several feet above the highest present lakes level.

Lastly we find all over the island indications of erosive activity by the sea at various levels above present sea-level: erosion benches, notches, platforms, and raised beaches. In this respect Rottnest Island is of outstanding interest and there is probably no better place in Western Australia for the study of recent movements of sea-level. Brief references to wave-cut platforms, undercut lake cliffs, and "raised" shell beds may be found in papers, chiefly concerned with mainland features, by Somerville (1921), Aurousseau and Budge (1921), and by Clarke (1926), but no systematic description of these features has as yet been attempted.

Tides and Levels of Reference

As everywhere along the coasts of south-western Australia, the tides at Rottnest Island are irregular and highly variable. "Between North-West Cape and Cape Leeuwin, the tides are greatly influenced by the wind, varying as much as 2 feet with off-shore and on-shore winds, the former reducing the sea-level. The rise and fall varies from 2 to 5 feet. The higher sea-level is attained in June and exceeds the lower sea-level, which is attained in November, by about 2 feet" (*Australia Pilot*, Vol. V).

It is common practice to record the position of shore-line features with reference to either mean sea-level or else low water level or Admiralty Datum. Under certain conditions this procedure is apt to lead to confusion, because, depending on the range of the tides, synchronous and homologous shore features may appear at very different heights above mean sea-level or above datum. The same sea

might heap up a beach ridge 5 feet above datum in one place along a coast and at 25 feet or 35 feet above datum a few hundred miles farther on. However, in both places the position of the beach ridge would be at or slightly above high water level and it seems, therefore, more natural to fix the height of shore line features with reference to that tide level to which they owe their origin. High water level

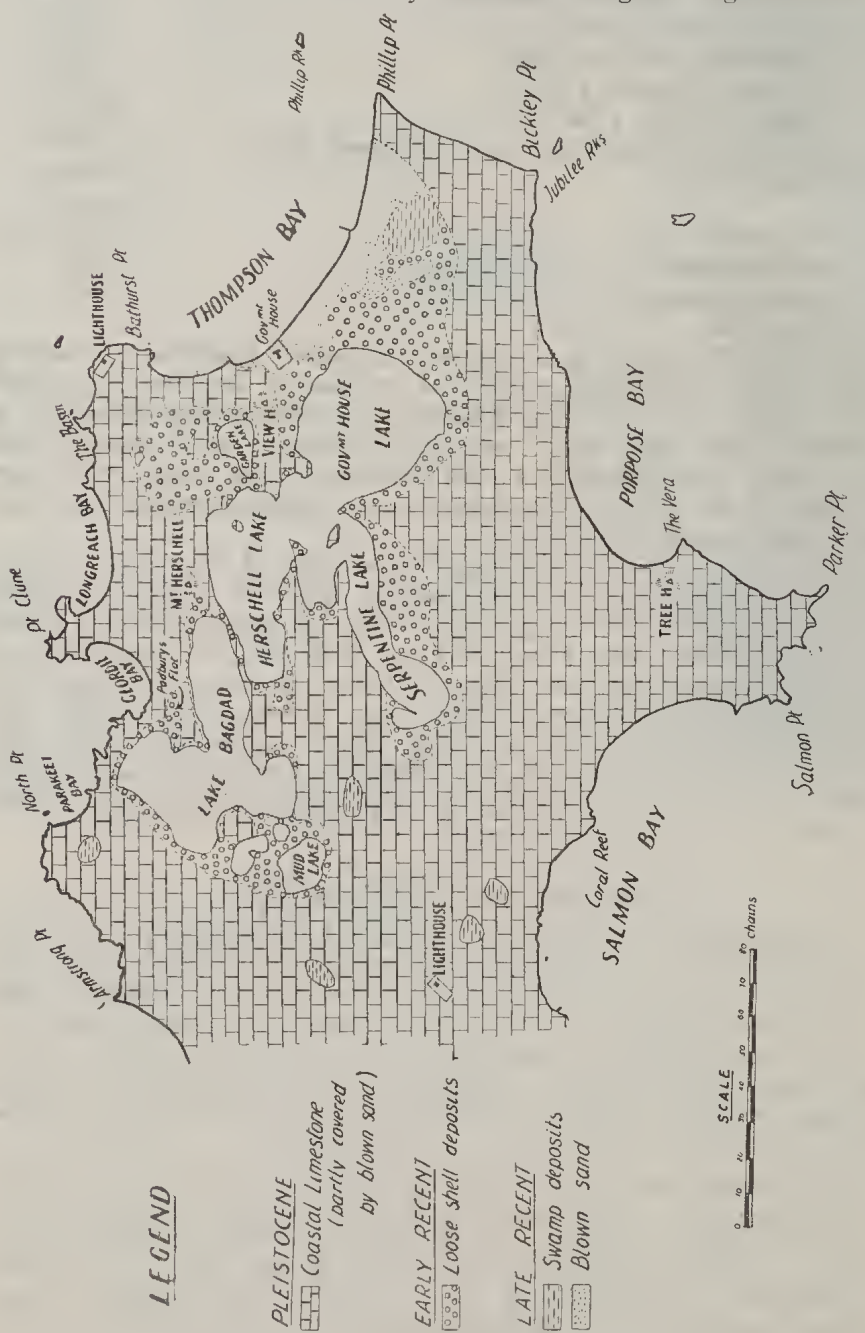

Fig. 2.—Geological map of eastern portion of Rottnest Island. (North is left.)

springs (H.W.L.S.) should be the level of reference for such features as beach ridges; low water level springs (L.W.L.S.) should be the level of reference for rock benches and coral reef tops, and so on. In case of doubt recourse could always be had to L.W.L.S. or Admiralty datum. In all cases a clear statement of the tidal conditions in the area under consideration should accompany or precede the description of shore line features.

All levels recorded in this paper were measured with an Abney level, but the tidal range on Rottnest Island being small and the time of arrival of the tides irregular, high water marks are usually neither clear nor very reliable. An error of one foot, or even two feet, may therefore be easily introduced in measurements which have high water level as their level of reference. In general, it may be assumed that in this paper H.W.L.S. is 4-5 feet, L.W.L.S. 0-1 foot above datum.

Coastal Limestone Series

The bulk of Rottnest Island consists of limestones and calcareous sandstones of the Coastal Limestone Series. Some of these rocks are marine, some are of aeolian origin, but the latter by far outweigh the former in importance. Dune limestones crop out in many places on the island and form most of the coastal cliffs. In some places the dune limestone can be seen to rest on marine, fossiliferous limestone. A deep bore has penetrated this limestone series to a depth of 200 feet below sea level, so that it may be assumed that the sea-floor in the vicinity of the island, approximately down to the 30 fathom line, consists of the same rocks.

The best place to study the older marine limestones of the island is Salmon Bay, in the middle of the south coast.

The Fossil Coral Reef in Salmon Bay

In the middle of Salmon Bay, on the south side of the island, is a low, rather inconspicuous, limestone cliff, forming an exposure about 300 yards long. This cliff rises from a limestone platform at approximately low water level, the platform sloping seaward at a low angle. At approximately mean high water level there is a narrow bench not more than a few feet wide and just above this level the cliff is in most places strongly undercut. The top of the cliff is almost horizontal at a height of about 10 feet above L.W.L.S. (Plate V, fig. 1).

The eastern half of the cliff consists of an emerged coral reef which rises to heights between 6 ft. 6 in. and 8 ft. 3 in. above the low water level platform. This platform continues to the east of the cliff where it can be followed at and below L.W.L. under a cover of beach sand. As far as can be seen it consists of solid coral limestone for a distance of at least another 30 or 40 yards and the coral reef must originally have extended in this direction. The predominating forms in the reef limestone are branching species of *Acropora* mixed with some foliose types, and in some places large colonies of *Platygyra lamellina* and of *Favites favosus* may be seen.

The thickness of this reef is possibly not great, because in some places it does not seem to extend below L.W.L. and can be seen to be underlain by calcareous, fossiliferous, though non-coralliferous, sandstone.

The slightly irregular surface of the reef is overlain by bedded, non-coralliferous limestone, or calcareous sandstone, which has a

rather uniform thickness of 2 ft. 9 in. This bed contains many shells, particularly gastropods, among which *Turbo stamineus* is very common.

The reef limestone does not extend along the entire length of the cliff. At about 500 feet from the eastern end of the cliff it grades into calcareous sandstone with shelly fossils which for some distance from the edge of the reef limestone contains some coral boulders, obviously derived from the old reef (fig. 3).

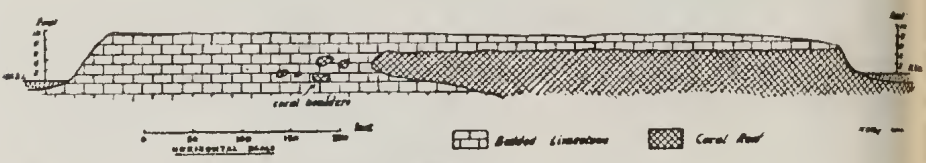

Fig. 3.—Section of limestone cliff with fossil coral reef at Salmon Bay.

Other Marine Limestones

Marine fossiliferous limestones or calcareous sandstones are found in some places, but their relationship with the dune limestones is not always clear. In the western half of Geordie Bay there are limestones with *Katelysia, Cardium,* and *Polinices* to a height of 1½-2 feet above H.W.L. In Thompson Bay, about 100 yards west of the main jetty, fossiliferous limestones, mainly containing *Katelysia,* rise from L.W.L. inshore to a height somewhat above H.W.L. However, in neither place can the relationships of these rocks with the dune limestones be established. Away from the shore, solid limestone with pelecypods occurs 8-9 feet above H.W.L. on the east side of the spur separating Government House Lake from Serpentine Lake, and a narrow ridge of shell limestone, rising to about 5 feet above H.W.L., separates Padbury's Flat from the eastern arm of Lake Bagdad. From their general occurrence it is likely that these two deposits form part of the Coastal Limestone Series and are older than the surrounding dune limestones.

Elsewhere limestones largely made up of shell grit are met with at or slightly above H.W.L., *e.g.,* along the shores of Wilson Bay.

Dune Limestones

Dune limestones make up the bulk of Rottnest Island. Since limestones of this type have a wide distribution along the coasts of Western Australia and have been discussed by me in two recent publications (1947 a and b), little need be said about them here. Characteristic outcrops can be seen everywhere on the island. A particularly instructive and easily accessible section may be studied at Bathurst Point, at the north-western end of Thompson Bay. Certain layers of the limestone are here penetrated by "root structures," generally calcareous secondary fillings of cavities left by the decay of roots of ancient vegetation—a characteristic feature of these dune limestones in all parts of Western Australia. Such root structures may be seen in other parts of the island, *e.g.,* at Strickland Bay, at Vera Rock, and at Salmon Point, and in some places the layers containing them may be seen to disappear below sea level.

Another interesting feature of the section at Bathurst Point is the existence of two generations of dune limestones. Just north of the lighthouse a lower cross-bedded grey limestone is separated from an upper, whitish, friable limestone, dipping 25° S., by a somewhat irregular hardened layer which in every respect resembles the travertine crust which is now found on the surface of many dune limestones on the mainland. Apparently sufficient time elapsed between the formation of the two dune limestones at Bathurst Point to allow a travertine crust to develop on the earlier dune, before it was buried by the second.

Very similar conditions can be observed at Vera Rock, on the south coast. A feature which adds to the interest of this locality is the covering of recent blown calcareous sand with partly travertine-encrusted roots of living trees, demonstrating a dune limestone with root structures *in statu nascendi*.

In general the dune limestones are characterized by the prevalence of steeply dipping ("foreset") beds, mostly dipping at 20° to 25° in various directions. In many places such steeply dipping beds are found down to and below L.W.L.

The dune limestones are uniformly fine grained rocks, consisting mostly of fragments of shells and other organic remains, with a varying admixture of quartz grains. Occasionally, however, coarser shell grit and larger quartz grains were blown up high. An interesting patch of such material was found about 60 feet above S.L. on a hill east of Mt. Herschell.

Age and Correlation of the Coastal Limestone

The geological section at Salmon Bay is of considerable interest because it resembles closely the section of the older limestones of the Abrolhos Islands, 300 miles farther north (Teichert 1947a). The major islands of this group are characterized by a foundation of solid reef limestone, overlain by on the average about 3 feet of non-coralline limestone, containing a shelly fossil fauna. The tops of these shell limestone platforms are as a rule situated about 10 feet above H.W.L., that is, at the same height as the top of the non-coralline limestone in the Salmon Bay cliff. A small coral reef on the mainland coast at Dongarra, 30 miles south of Geraldton, occupies a very similar position (Teichert 1947a), and it seems an obvious conclusion that the older reef limestones of the Abrolhos Islands, the Dongarra reef, and the Salmon Bay reef of Rottnest Island are all of the same age. I have previously suggested that they were formed during an interglacial period of the Pleistocene, when the sea-level stood higher than now and the climate was possibly slightly warmer. Reef building corals, including a vigorous growth of *Acropora*, then found a favourable environment 300 miles south of the present southern limit of the coral reef belt.

Even to-day a fairly vigorous growth of reef corals is found in a few places around Rottnest Island. In the tidal zone near Cape Vlaming there are many healthy colonies of *Pocillopora*, and *Siderastraea radians* also occurs there. Numerous patches of vividly coloured *Pocillopora* colonies can be seen in the vicinity of Cape Parker and, no doubt, they must occur elsewhere along the coasts of

the island. On the beach near Parker Point I found a bleached, though very fresh-looking specimen of *Platygyra* ("*Meandrina*") *lamellina* which makes it seem likely that this typical reef coral still survives in the waters around Rottnest.

The stratigraphical position of the dune limestones of Rottnest Island corresponds to that of the dune limestones of the Abrolhos Islands and of the mainland of Western Australia. Observations on Rottnest Island strongly suggest that the dune limestones were deposited at a time when the water level stood lower than now, for almost everywhere they can be seen to extend below L.W.L. and they are now being vigorously attacked by marine erosion. Age and correlation of these rocks have been discussed more fully elsewhere (1947 a and b): they were regarded as formations of one of the later glacial stages, probably the last, of the Pleistocene, built up at a time when much of the limestone-covered continental shelf was exposed above sea-level and thus furnished material for extensive dune formations along a thousand-mile stretch of mainland coast. Dunes were thus accumulated on the promontory formed by the 10-fathom line and elsewhere on the continental shelf.

The Shell Deposits of the Lake Area

The shores of the salt lakes are lined with fossiliferous rocks and loose deposits in which shells of pelecypods and gastropods predominate, in most places to such an extent that we may speak of "shell deposits" or "coquina beds." Almost any point on the lake shores is equally well suited for the study of these formations, although they are better developed in some places than in others. Along certain shores they form but a narrow fringe, as, *e.g.*, on the north coasts of Lakes Bagdad and Herschell. Elsewhere, for example, east of Lake Bagdad and along the south side of Serpentine Lake, they form wider belts. Also, a low flat area north of Garden Lake, almost extending as far as the sea to the north and separated from the "Basin" only by a narrow ridge of dune limestone, is entirely covered with deposits of the same kind. East of Government House Lake is another large flat area, part of which is used as an aerodrome, extending as far and beyond Bickley Swamp; this flat is also covered with shell deposits, though of a somewhat different type.

Whereas everywhere else the shell beds are surrounded by dune limestone ridges, towards the north-east, between Government House Lake and Thompson Bay they are covered by more recent, loose sand dunes which form a narrow belt along the coast between a point somewhat N.W. of the old Government House and the vicinity of Philip Point. Strongly eroded dune limestone crops out on the coast a short distance west of the Point.

Along the lake shores the shell deposits are cemented into limestone, apparently because here they are alternately submerged and exposed with the changing seasons. In summer the lake level falls and exposes a fringe or platform of fossiliferous limestone from which large collections can be made. The position of this platform, as mentioned earlier, is approximately at, or perhaps slightly higher than M.S.L. The lakes are, of course, now quite devoid of molluscan life, the salinity exceeding 10% in the summer.

Away from the lake shores the deposits are uncemented and rise to varying heights. They were found in the highest position on a small flat in the eastern continuation of Lake Bagdad, just south-west of Mount Herschell. From the limestone platform on the lake shore the ground rises gradually to a terrace about 9 feet high (approximately 6-7 feet above H.W.L.S.) which consists entirely of densely packed shells, mostly rather large forms such as *Marcia, Katelysia, Bullaria, Polinices,* but also *Peronidella* and regular echinoids. From this terrace shell beds rise further to a height of 12½ feet (about 10 feet above H.W.L.S.), but these higher deposits consist of shell grit and small shells, mostly gastropods of the *Coxiella* type. This is the highest point at which such deposits have been found.

On Padbury's Flat, north of Lake Bagdad, loose shell deposits were found up to a height of 5 ft. 3 in. above the lake shore platform (about 3 feet above H.W.L.S.). On the north-east side of Government House Lake, south-east of View Hill, there are distinct beach ridges of loose shell material, but their height was not measured. Finally, the surface of the flat east of Government House Lake is 6 ft. 3 in. above the lake shore platform (8 to 9 feet above L.W.L.S.).

As to the composition of the coquina deposits in various parts of the island, no close analysis has as yet been made. Reath, in 1925, listed the following molluscan species from "sub-recent" deposits on Rottnest Island:

PELECYPODA.—*Brachyodontes erosus* Lam., *Cardita* sp. *Dosinia lucinalis* Lam., *Marcia peronii* Lam., *Veneruplis planicosta* Desh., *Amphidesma praecisa* Reeve, *Nausitoria saulii* Wright.

GASTROPODA.—*Cantharidus nitens* Kiener, *Patelloidea connoidea* Quay and Gainard, *Bembicium melanostoma, Bittium estuarium* Tate. *Tonna variegata* Ten. Woods, *Arcularia victoriana* Iredale, *A. rufula* Kiener.

It is probable that most, if not all, of these come from the shell deposits of the salt lake area, though even a preliminary survey of the shell deposits shows that the list must be rather incomplete*. However, I am not in a position to make many additions, but other forces noticed included *Ostrea, Chama, Vermetus,* and *Turbo.*

Besides the shelly fauna, echinoids are commonly found, particularly fragments of the large irregular genus *Peronidella.* In the vicinity of the bathing jetty on the shore of Government House Lake there is a large colony of *Favites* embedded in the limestone—the only fossil coral seen on the island outside the Salmon Bay coral reef.

The greatest variety of species is as a rule found in the immediate vicinity of the present lakes and up to a few feet above the lake shore platform. The highest deposits seem to have an impoverished fauna. It has already been mentioned that the deposits at heights between 9 and 12½ feet east of Lake Bagdad consist largely of *Coxiella.* Similarly, the deposits east of Government House Lake may be described as shell sand in which *Coxiella* is common, although there is a fair admixture of pelecypod shells, chiefly *Katelysia.* In the eastern extension of this flat is Bickley Swamp which is underlain by a marly deposit containing some *Coxiella* shells.

* It must be remembered that the collections studied by Reath came from several deposits of different ages. Some came from beds definitely older than the duue limestones (Peppermint Grove, Minim Cove) and therefore of Pleistocene age.

Marine Benches and Other Erosion Marks

Perhaps the most striking features of Rottnest Island are the many signs of marine erosion at various heights above sea-level, found in many parts of the outer coast, but more particularly around the shores of the salt lakes. It is easily possible to distinguish three levels of marine erosion which may be known as "high," "intermediate," and "low" respectively, although in a few cases certain erosional or other features cannot be correlated with certainty with any of these levels.

One of the localities where all three erosion levels may be observd in most perfect preservation is on the north shore of Government House Lake, close to the Causeway (fig. 4; pl. V, fig. 2). Here dune lime-

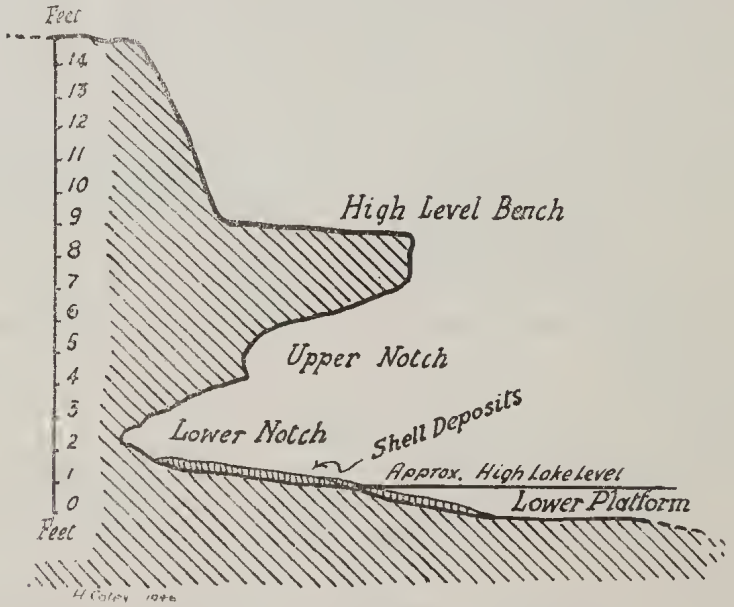

Fig. 4.—Profile of shore cliff, Government House Lake, near Causeway.

stone with south-east dipping stratification is exposed in a cliff which forms an overhanging ledge several feet wide. This ledge is perfectly flat, carved out of the limestone, and is situated about 8 ft. 9 in. above the limestone platform surrounding the lake, or about 11 feet above L.W.L. Below this ledge there is a well-marked erosion notch the base of which is 4 ft. 6 in. below the level of the platform. Farther down near the foot of the cliff the limestone is much more strongly eroded by a deeply incised notch, the base of which is 2 ft. 6 in. below the base of the upper notch and about 1 ft. 9 in. above the lake shore platform. This platform is situated at or perhaps slightly above mean sea-level.

A similar cliff profile, although not often so well developed, may be seen elsewhere along the lake shores, for example on some small islets between Lakes Bagdad and Herschell, and on the north side of Serpentine Lake.

The characteristics of these three erosion levels may be amplified by some further observations:

High Level Bench.—This characteristic feature is preserved in many parts of the island along the outer coast as well as along the

lake shores and has already been briefly referred to in publications by Somerville (1921) and by Clarke (1926). It is no doubt the remnant of a normal shore platform (Pl. VI, figs. 1, 2). Along the outer coast its surface is at about 10 feet above present L.W.L. and along the lakes it is 8 to 9 feet above the lake shore platform, or about 10 to 11 feet above L.W.L. The bench is particularly well preserved in the vicinity of Cape Vlaming, in Wilson Bay, in various places along Strickland Bay and between North Point and Armstrong Point, but also in many other places along the outer coast. In the lake area it shows up well along the north shore of Serpentine Lake, on the south side of Lake Herschell and around the shores of the eastern arm of Lake Bagdad. It is generally cut into cross-bedded or steeply dipping dune limestones and differential erosion plays no part in its formation.

Associated with this level are probably the highest shell deposits mentioned above, especially those rising to 12½ feet above the lake shore platform in the eastern extension of Lake Bagdad.

Intermediate Level.—In the cliff near the Causeway, this level is represented by the "upper notch," about 4 feet above that of the lake shore platform. Except near the Causeway this level is particularly well preserved between Lakes Bagdad and Herschell and indications of it may be seen elsewhere. In some places, however, no traces of it can be detected as, *e.g.*, along the south shore of Lake Bagdad. The shallowness of this notch together with its erratic distribution around the lakes suggests that the sea did not remain long at the level at which the notch was cut. Owing to the small size of the lakes wave erosion must be rather ineffective and the upper as well as the lower notch may be regarded as essentially due to solution.

Associated with the upper notch level are probably many of the shell deposits, for example, those of the flat ("aerodrome") east of Government House Lake which rises to about 6 feet above the lake shore platform. The shell beds of Padbury's Flat and the lower coquina deposits east of Lake Bagdad are found at about the same height and probably the shell sand ridges on the north coast of Government House Lake, south-east of View Hill, also belong here.

Along the outer coast, as may indeed be expected, most traces of this erosion level have been obliterated. However, in a particularly sheltered place in the north-east corner of Thompson Bay there are remnants of a fossiliferous conglomerate adhering to the cliff at a height of about 4½ feet above M.S.L. which corresponds approximately to the position of the upper notch in the shore cliff profile of the lakes.

On the west side of Wilson Bay there is a marked bench situated at about H.W.L.S. This seems to be the vestige of a normal shore platform made by the same sea which was responsible for the upper notch of the lake cliffs.

Low Level.—This is represented by the lower notch in the lake shore profile which is well preserved in a great many places. Next to the high level bench it is the most characteristic feature of the lake shores. Its position is between 1 and 2 feet above highest lake level. Its exact position relative to sea-level (M.S.L. or Datum) could only be established by an instrumental survey, but indications are that this

notch is in a position corresponding to present H.W.L. and probably about 2½ feet higher than the erosion notch produced by the action of the sea at present mean sea-level around the outer coast of the island.

This notch, too, must be a solution feature. It is in places several feet deep, although the destructive power of the waves of these small lakes must be negligible.

Features associated with this lower notch are the lowest shell deposits and the limestone platform surrounding the lake shores. This is an erosion platform truncating dune limestones as is well seen on the north side of Government House Lake, near the Causeway. It is dry in normal summers, when the lake level falls. In most places the platform is covered with more recently cemented calcareous sand and shell grit containing many shelly and other fossils as described above. On the narrow shelf between Lakes Bagdad and Herschell an interesting "edgewise conglomerate" can be seen formed of broken-up thin laminae of dune limestone.

No traces of this erosion level have been preserved anywhere along the outer coast.

Information regarding former positions of sea-level may be summed up in the following table:

TABLE 1. FEATURES CAUSALLY CONNECTED WITH:—

High-water Level	*Height above H.W.L.*	*Mean-Water Level*	*Height above M.W.L.*	*Low-Water Level*	*Height above L.W.L.*
Highest shell beds east of Lake Bagdad.	10 ft.			Upper platform of outer coast and around salt lakes.	10-11 ft.
Intermediate shell beds (partly associated with lower levels).	3-6 ft.	Upper notch of salt lake cliffs.	4-5 ft.	High-water level bench in Wilson's Bay.	5 ft.
		Fossiliferous conglomerate, N.W. corner of Thompson Bay.	abt. 5 ft.		
		Lower notch of salt lake cliffs.	abt. 2 ft.	Lakeshore platform and lowest shell deposits.	2-3 ft.

On the mainland along the Swan and Helena Rivers Aurousseau and Budge (1921) established the presence of three erosion cycles, called Guildford, West Midland and Helena, each initiated by a eustatic lowering of sea-level. From Aurousseau and Budge's data it would appear that the sea-level stands were as follows:

pre-Guildford . . . . . 22 ft. above present.
pre-West Midland . . . . . 14 „ „ „
pre-Helena . . . . . 7 „ „ „

While there is no evidence on Rottnest Island of the pre-Guildford stand, the pre-West Midland stand is represented by the high-level platforms, as indeed already suggested by Aurousseau and Budge, although as we have seen sea-level might have been somewhat lower than indicated by those authors. The shell beds and undercut cliffs are correlated by Aurousseau and Budge with the Helena cycle, although they do not mention the existence of a double notch nor the presence

of shell beds at greatly varying heights. It would seem then that the pre-Helena stand corresponds to our intermediate level on Rottnest and is responsible for the upper notch of the lake shores and associated features.

Evidence of the lowest 2 ft. stand has yet to be discovered on the mainland.

Outline of Geological History

The oldest rocks of Rottnest Island are probably the coral reef limestone of Salmon Bay and associated rocks, dating back to one of the interglacial periods of the Pleistocene. Limestone forms the foundation of the island down to a depth of 200 feet below sea-level, but the nature of these rocks is not known in detail. At the time of the formation of the Salmon Bay reef sea-level stood at least 8 feet above the present, although it is, of course, entirely possible that the reef stood originally higher and was subsequently denuded to its present level. Owing to some change in water level or temperature or both, coral growth was then interrupted and non-coralline limestone was deposited on the eroded surface of the coral reef.

Subsequently sea-level must have fallen and the old limestone foundation greatly eroded and denuded and calcareous dunes were swept together on top and around the erosion remnants. At that time much of the shelf surrounding the present island must have been dry land, supplying material for the large dune formations which could hardly have been accumulated under present-day conditions. It is also evident that in many places these old dunes were deposited and covered with vegetation in a position below present sea-level.

The dunes were heaped up in an irregular manner into ridges and hummocks of different heights. No doubt the dune topography extends below sea-level in the vicinity of the island and the many reefs near its coasts are but the tops of submerged and partly destroyed limestone dunes. A group of dunes in the south remained separated from a dune ridge in the north by a series of depressions, now reaching 30 feet below sea-level and occupied by salt lakes.

In general it may be concluded that the dunes were built up on a platform the approximate outline of which is now indicated by the 5-fathom line, because inside this line the sea floor is very irregular, but beyond it the bottom slopes away gradually to the 10-fathom line and farther (fig. 5). Also, 5 fathoms is the maximum depth of Government House Lake. Other lakes may have similar depths.

After the deposition and cementation of the dune limestones the sea rose to about 10 feet above its present level and from general evidence elsewhere in Western Australia (Teichert 1947a) there is reason to suppose that this rise was part of the general eustatic upward movement of sea-level after the end of the Pleistocene. The group of calcareous dunes, now hardened into dune limestones, became an island, and the dune valleys described above were converted into a deep and ramified inlet of the sea. With its entrance facing landward and away from the direction of the prevailing winds, this inlet was in an extremely sheltered position and offered favourable living con-

ditions to dense and varied animal communities. At certain times these communities became impoverished, and euryhaline forms such as *Coxiella* multiplied at the expense of others which disappeared. From this it must probably be concluded that the old dune valley was not entirely open to the east, but was barred by somewhat lower limestone dunes which now formed a bar across the entrance to the inlet. The salinity of the water in the inlet was therefore subjected to changes caused either by changes in the rate of evaporation, or by very slight changes of sea-level, or perhaps even by the accumulation of shifting sand bars across its entrance.

Sea-level must have remained at this level for a time sufficiently long to allow fairly extensive bench cutting to take place. It then subsided by about 5 or 6 feet, remaining at the new level for a comparatively short period only, sufficient to leave some traces of erosion (notch-cutting) in the cliffs surrounding the inlet (upper notch).

At a still later stage the sea subsided further to a position about 2 feet (or very slightly more) above the present level and stayed there sufficiently long to be able to undercut deeply the cliffs surrounding the inlet. The lower notch in the lake shore profile is the result of this period. Sand bars must now have formed at the entrance to the inlet and tended to shut it off from the open sea, and when sea-level finally receded to its present position the inlet became a series of interconnected lakes in which owing to the high salinity (10% in summer) no molluscan life now exists and a low ridge of sand dunes was formed on top of the bar separating these lakes from the sea.

As long as the inlet maintained an open connection with the sea and molluscan life was possible, shell beds were formed at all sea-level stands. As may be seen from Reath's list (1925) the species composing these shell beds are now mainly found around the south-west coast of Western Australia and it seems that no noticeable change in water temperature can have taken place in recent times. The warm water species in the fauna studied by Reath probably all came from the shell deposits of Peppermint Grove, Minim Cove and related beds which underlie the dune limestones and belong to an interglacial stage of the Pleistocene.

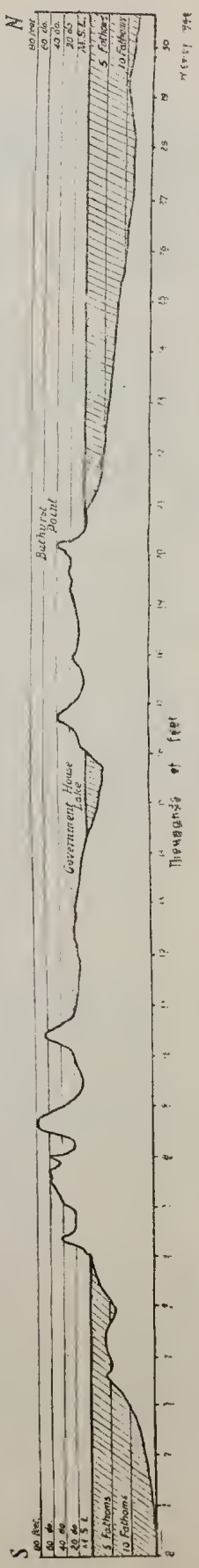

Fig. 5.—N.—S. profile through Rottnest Island.

Conclusions

Rottnest Island lies off the edge of the Precambrian shield of Western Australia, one of the great stable units of the earth's crust. It should, therefore, be eminently suited for the purpose of studying eustatic sea-level changes during recent geological times. The only other area in Western Australia where similarly detailed investigations of this kind have been made are the Abrolhos Islands 300 to 400 miles farther north (Teichert 1947a). A comparison of geological events and resulting rock formations in the two areas is given in the following table which also contains a few references to corresponding features on the mainland. The latter are unfortunately very limited and incomplete, because the coastal physiography of Western Australia has so far received very little attention.

There is good general agreement between Rottnest Island and the Abrolhos Group and the evidence fits smoothly into the now widely recognized sequence of late Pleistocene and Recent sea-level shifts. Some correlations with river terraces of the Swan-Helena drainage system have been indicated elsewhere in the text.

TABLE 2. GEOLOGICAL EVENTS AND ROCK FORMATIONS ON ROTTNEST AND ABROLHOS ISLANDS.

	Rottnest Is.	*Abrolhos Is.*	Selected mainland localities.	Sea-level.
RECENT	Low erosion level (lower notch and lake shore platform).	Low-level beach ridges.		Sinking to present level.
	Intermediate erosion level (upper notch, &c.).	Shingle limestone of Pelsart Isl.	Notch 4-5 ft. above L.W.L. at Trigg Isl., Moore R., Jurien Bay*.	
	Highest coquina beds. High-level bench.	High-level beach ridges and negro-heads. High-level platform.	High-level Bench at Cottesloe (also at Trigg Is., Moore R., Jurien Bay*).	+ 10 to 20 ft.
PLEISTOCENE	Dune limestone.	Dune limestone.	Dune limestone.	Lower than —30ft.
	Shell-bearing limestones.	Shell limestone.	Emerged coral reefs of Dongarra and Onslow; Marine beds of Peppermint Grove, Mosman Park.	+ 20 ft. or slightly higher.
	Salmon Bay reef	Reef limestone foundation.		

* Personal communication by R. W. Fairbridge.

Some points in this table call for a special discussion. Interpretation of the geological record is complicated by the fact that at and above the 10-ft. level we find erosional and depositional features which must obviously be attributed to two widely separated geological periods, separated by the formation of the dune limestones. A few remarks may serve to explain this more clearly:

(1) The old coral reefs of the Abrolhos and Rottnest Islands, and also at Dongarra on the mainland coast, are truncated at about this level and the formation of the overlying fossiliferous non-coralline limestones followed at very much the same or a but slightly higher sea-level stand. This whole sequence is of Pleistocene age and was

deposited at a time when sea-level stood up to 20-25 feet higher than now. This corresponds well with Zeuner's Late Monasterian level for which ample evidence seems to exist in the Mediterranean, in western Europe, and elsewhere (Zeuner, 1945, p. 249). This was the lowest of all the interglacial sea-levels of the Pleistocene and belongs, according to Zeuner, to the last interglacial period (Riss-Würm). The time was about 125,000 years ago.

The dune limestones would have been formed at the time of eustatic regression during the ensuing last glacial ice-age (Würm). This conclusion seems entirely acceptable in the light of the Western Australian evidence.

(2) The geological evidence for this "Late Monasterian" level may easily overlap with or be camouflaged by the evidence for the post-glacial, early Recent, eustatic rise in sea-level of which, as we have seen, there is also ample evidence in Western Australia. During this time platforms were carved into the late glacial dune limestones and loose shells deposits were heaped up. This coincidence of the last interglacial and the early post-glacial sea-levels is a factor which probably deserves the greatest attention.

From evidence in many parts of the world, including the Abrolhos Islands, it has been concluded, as indeed first suggested by Daly, that the post-glacial rise of sea-level was of the order of 15 or 20 feet, but no signs of a sea-level higher than 10 or 11 feet have been detected on Rottnest Island. No explanation of this fact can be offered at this stage.

As regards the lowering of sea-level after the high stand in early Recent times it is necessary to call attention to some discrepancies in the evidence from Rottnest Island and from the Abrolhos Islands. From the mode of arrangement and preservation of the younger coral shingle beach ridges on some of the Abrolhos Islands I had been inclined to conclude (1947a) that the mid-Recent and later subsidence of sea-level took place gradually and continuously during the last 2,000 years or so and has now come to an end. On Rottnest Island as we have seen there is evidence of a lowering of sea-level by three steps, separated by two stillstand periods which have left their unmistakable traces in the cliffs. Further light on this problem can only be thrown by a more systematic investigation of the mainland coast of Western Australia between Cape Leeuwin and Geraldton.

Recent subsidence of sea-level by steps rather than as a gradual phenomenon has been advocated by several modern writers. In the Pacific Stearns (1941, 1945) recognized evidence for a "five-foot stand" and a "twenty-five-foot stand" of the sea. In the Great Barrier Reef Steers (1937) proved the existence of a "lower bench" indicating a recent 5-foot negative movement of sea-level. In the East Indies Kuenen (1933) found benches at 5-6½ feet and at 1½-3 feet above "mean water level." The lower one of these benches is probably to be correlated with our lower notch of the lake shore profile of Rottnest Island.

References

Aurousseau, M., and Budge, E. A.: The Terraces of the Swan and Helena Rivers and their Bearing on Recent Displacement of the Strand Line. *Jour. Roy. Soc. W.A.*, 7, (1920-21), pp. 24-43. 1921.

Figure 1.

Figure 2.